**Discussion**

***Bulk tank milk aerobic culture data* *by facility type***

As shown in Table 2, there were no significant differences in bacterial counts from bulk tank milk for *Staph.* species, coliforms, non-*ag Strep.,* or *Staph aureus* between the three facility types. The absence of any significant difference in the levels of *Staph.* spp., coliforms, and non-*ag Strep.* in BTM between facility types suggests that milk from cows housed in bedded packs is not more likely to have higher amounts of these environmental mastitis pathogens, despite being loose-housed on deeply-bedded organic materials.

Although the mean CFU/mL of *Staph.* spp. in bulk tank milk was numerically higher for tiestall farms than freestalls or bedded packs, this group contained a substantial outlier (one farm with 665 CFU/mL). When the analysis was re-run without this farm included, the mean and SD for each of the three groups was much more similar [BP: 53 CFU/mL (49); FS: 66 CFU/mL (48); TS: 76 CFU/mL (60)]. The *Staph.* spp. count for the five bedded pack farms included in this study (53 CFU/mL, 95% CI: 10-96) was similar to previous work describing bulk tank milk quality for composting bedded packs in Minnesota. The six farms included in Lobeck et al. used mainly wood sawdust as a bedding source (with one using a wheat straw by‐product), which is similar to the current study (three of five using combination of wood chips shavings, and straw/hay, two using exclusively sawdust/shavings). The six farms included in Shane et al. 2010 bedded with a variety of “alternative” organic materials, including straw by-products, soybean stubble, and oat hulls. Although the aerobic culture methodology differs slightly between the current study and previous work, all three studies collected bulk tank milk over the winter months. Lobeck et al. 2012 found a mean of 26.1 CFU (95% CI: 2-443) and Shane 2010 et al. found a range of 0-108 CFU/mL for *Staph.* spp. from BTM collected during the winter from six composting bedded pack farms.

Similar to *Staph.* spp., the mean non-*ag Strep* counts for tiestalls was numerically higher than the other 2 facility types, but this was due to a significant outlier. Without this outlier, the mean non-*ag Strep.* counts for each of the three facility types were more similar, although tiestalls were still somewhat higher [BP: 39 CFU/mL (25); FS: 89 CFU/mL (98); TS: 145 CFU/mL (110)]. Non-*ag* *Strep.* counts in BTM for bedded packs in the current study were much lower than those found from Minnesota composting bedded packs in the winter. Shane et al. 2010 reported a range of non-*ag Strep.* counts of 98-48,400 CFU/mL for six farms, and Lobeck et al. 2012 reported a mean of 911 CFU/mL (95% CI: 138-6,011). The mean non-*ag Strep.* counts for bedded pack farms included in the current study was 39 CFU/mL (95% CI: 17-61). A study from Barberg et al. (2007) describing milk quality on composting bedded packs in Minnesota notes that 6/12 farms sampled had “high” levels of non-*ag Strep.,* but do not give an actual number. Furthermore, the overall non-*ag Strep.* count for all farms included in the current study (156 CFU/mL, 95% CI: 42-271) was much lower than that for the overall *Strep.* count for all three facility types studied in Lobeck et al. 2012 (445 CFU/mL, 95% CI: 116-1704). As the overall non-*ag Strep*. counts for all farm types included in the Minnesota studies are higher than that found for all 21 farms in the current study, geographical variation in pathogen profiles may best explain this difference in BTM bacteriology.

All farms included in the study had very low levels of coliforms in bulk tank milk (1.2 CFU/mL, 95% CI: 0.3-2.1), indicating excellent hygiene practices at milking time. Bedded pack farms in the current study had very low coliform counts in BTM (1 CFU/mL, 95% CI: 0-3), similar to those found for three compost bedded pack farms in a Brazilian study (2.8 CFU/mL; Fávero et. al, 2015). However, these low coliform counts are in contrast with previous work describing BTM quality for this kind of facility in the United States. Coliform counts for bedded packs in Minnesota in the winter ranged from 15-1,128 CFU/mL (Shane et al. 2010), and had a mean of 63.7 CFU/mL (95% CI: 6-735) for the six bedded packs included in Lobeck et al. 2012. Although sampled during summer months, Barberg et al. 2007 found that 5/12 bedded packs sampled had “high” levels of coliforms in BTM, contributing to their conclusion that “special attention to cow preparation procedures at milking time are a must for achieving satisfactory milk quality when cows are housed in compost dairy barns.”

Although not statistically significant, the mean *Staph. aureus* count for bedded pack farms was numerically smaller than that for tiestalls and freestalls. Additionally, the bedded pack category had the highest proportion of farms that with BTM negative for *Staph. aureus* (60% for BP, vs. 33.3% for both TS and FS). As *Staph aureus* is categorized as mainly a contagious mastitis pathogen, on-farm prevalence more likely is a function of milking procedure hygiene and other management practices associated with limiting cow-to-cow transmission than environmental factors (i.e., bedding material type and hygiene). The lower prevalence of *Staph. aureus* on bedded pack farms in the current study may be a function of confounding. Producers who may be early adapters of a less-familiar housing type and who may be more innovative and open to newer technologies are likely more progressive generally in their management style, and therefore more likely to have implemented stricter control programs for contagious mastitis pathogens. Prevalence of *Staph. aureus* was similar between the five VT bedded pack farms in the current study (9 CFU/mL, 95% CI: 0-21) and the six bedded packs described in Lobeck et al. 2012 (6.2 CFU/mL, 95% CI: 1.3-30.1). Farm-level prevalence of *Staph. aureus* was also fairly low for bedded packs studied in Shane et al. 2010 (3/6 farms BTM negative) and Barberg et al. 2007 (only 1/12 farms with a “high” level of *Staph. aureus*). Overall, the population of 21 farms in the current study had a higher amount of *Staph. aureus* in BTM than that of the 18 Minnesota farms described in Shane et al. 2010 (43.6 CFU/mL, 95% CI 14-73; vs. 17.3 CFU/mL, 95% CI: 3.3-91.2).

Analysis of a single bulk tank milk sample from a farm is a simple, convenient, and relatively inexpensive way to capture a snapshot of current milk quality and animal health on a farm, and can be a highly specific (albeit poorly sensitive) screening test for the major contagious mastitis pathogens *Staph. aureus* and *Strep. agalactiae* (Godkin and Leslie, 1993). However, a single bulk tank sample does not provide information about milk quality and mastitis at the individual cow level, nor does it give any insight into the long-term, consistent patterns of that farm’s milk quality as repeated BTM samplings may do (Jayarao and Wolfgang, 2003). With the financial constraints of research studies on dairy farms, the limitations inherent in performing analysis of a single bulk tank milk sample from each farm were a trade-off for the ability to get a picture of milk quality on a larger number of farms included in the study.

Can be a highly specific, poorly sensitive test to screen herds for major mastitis pathogens (*Staph. aureus, Strep. uberis)*; if present in BTM culture, reliably indicate intramammary infections due to that pathogen on the farm. However, environmental bacteria unlikely to be indicative of proportion of cows infected with these organisms. May enter into BTM from milk with an intramammary infection, but also can get into BTM from non-specific contamination; can maybe indicate general level of environmental and milking hygiene in the herd … Bacteria present in milk samples from the bulk tank may originate from infected udders, from teat and udder surfaces, or from a variety of other environmental sources

***Bulk tank milk udder health and hygiene measures by facility type***

One theme emerging from this work is that farms with deeper bedding had more favorable udder hygiene.Increased bedding depth measures also tended to be associated with lower mean udder hygiene scores. Cows housed on some type of deep bedding (deeply-bedded stalls or bedded pack) had lower average hygiene scores than those housed on stalls with a smaller amount of bedding over a mattress or concrete surface (p = 0.06). This agrees with previous work in freestall barns, from Cook et al 2016 (prevalence of dirty udders was 13% lower for farms using deep bedding verses stalls with mats), de Vries et al 2015 (deep-bedding vs. mat/mattress reduced likelihood of a cow having a dirty hindquarter by half), and Robles et al 2020 (farms with mattress-based stalls had a higher prevalence of cows with dirty upper legs/flanks vs. those using a deep bedding system, often inorganic sand). However, limited work studying the effect of bedding depth in tiestalls found no difference between leg, flank, and udder hygiene of cows between deeply-bedded stalls (14 cm) and the control treatment (2-3 cm; Wolfe et al, 2018). For freestall and tiestall barns included in this study, there was a negative correlation between the depth of bedding in a stall and average udder hygiene score (p = 0.07). de Vries et al (2015) found no relationship between prevalence of dirty hindquarters and three different freestall bedding height groups (<0.56 cm, 0.56–1.75 cm, >1.75 cm), but there is much more opportunity for research to explore the relationship between stall bedding height and cow hygiene, especially in tiestall systems. Although sample size for the bedded pack group in this study was limited (n = 5), we found a negative correlation between depth of bedded pack and average udder hygiene score (p < 0.01), a relationship which has previously not been studied to the author’s knowledge.

Multiple measures of udder health in this work were related to udder hygiene, in accordance with the well-supported tenet that better cow hygiene is associated with better milk quality. Farms with lower mean udder hygiene scores and lower proportion of dirty udders tended to have lower % chronic IMI (p = 0.05) and lower % any IMI (p = 0.09). Additionally, having a lower proportion of dirty udders was associated with a lower weighted average linear score (p = 0.20), and farms that clipped or flamed udders on a regular basis tended to have fewer % chronic IMI (p = 0.16).This association between an animal’s hygiene and udder health is been well-documented, both at the cow level (for IMI presence: de Pinho 2012; for LS/SCC: Reneau, 2005, Dohmen, 2010, and Sant’Anna, 2011; for both LS and IMI: Schreiner and Ruegg, 2003) and at the herd-level (BTSCC: Barkema 1998; new IMI rate: Cook, 2002, average herd SCC, incidence clinical mastitis, and % new high SCC: Dohmen, 2010). Of particular interest to the current study, Fávero et al (2015) found that in a study carried out on 3 bedded pack farms in Brazil, the odds of an incident case of subclinical mastitis (SCC ≥ 200,000 cells/mL), and of a cow having a prevalent case of subclinical mastitis, increased 32% and 16% for each one-unit increase in leg cleanliness score, respectively. Curiously, although leg cleanliness score was associated with both mastitis indices, udder hygiene score was not found to have a significant association.

A third predominant theme to emerge from the univariate regression results in this work is that farms using deeper bedding had better milk quality outcomes.As stall bedding depth in tiestalls and freestalls increased, farms showed a tendency toward having a lower bulk tank somatic cell count (p = 0.17), lower % new IMI (p =0.02), lower % any IMI (p = 0.01), and a lower weighted average LS (p = 0.05). Additionally, farms that used deep-bedded stalls or a bedded pack tended to have a lower BTSCC than those using stalls with mattresses or a concrete base (p = 0.14). Although there is an established recommendation of 15 cm for deep bedding of freestalls (Bickert, 2000; Cook, 2002), but this depth appears to be based on optimizing cow comfort in deep-bedded freestalls with no relevance for udder hygiene or health considerations. There is very limited work exploring ideal bedding material depth for tiestall barns (Tucker, 2004; Tucker, 2009), and this is again solely focused on the important consideration of cow comfort. As is the experience of the authors, and is stated elsewhere in a literature review by McPherson (2020), “…very little research has investigated the effect of bedding depth on cow cleanliness,” or considerations around udder health outcomes. It is likely that the effect seen in the current work of deeper bedding and better udder health outcomes is mediated through the preestablished effects of (1) deeper bedding leading to improved hygiene, and (2) improved hygiene resulting in better udder health. Therefore, the opportunity exists for research exploring optimal stall bedding depths of different organic materials in tiestall barns focusing on mastitis and udder health outcomes. How deep do we need to bed tiestalls to keep moisture, and therefore bacteria, away from the udder as much as possible? However, it may be that recommending a particular depth of bedding to use for different types of organic material may not prove feasible, as the ideal amount would vary with many factors particular to a producer’s barn and bedding source (type of stall surface, presence/type of stall mat used, type of organic material, particle size, compressibility, percent dry matter, etc.).

We found no difference in udder hygiene measures (proportion of udders scored ≥3, average udder hygiene score) between the three facility types included in the study (tiestalls, freestalls, bedded packs). This finding is in accordance with previous work, which found that cow hygiene on bedded pack systems was comparable to traditional facility types primarily in Minnesota, Kentucky, and Brazil (Andrade, 2022; Eckelamp, 2016a; Eckelkamp, 2016b; Black, 2013; Costa, 2018; Shane, 2010; Barberg, 2007; Lobeck, 2011). In comparison to some previous work comparing hygiene of dairy cows between different facility types, only udder hygiene was measured in the current study. Other researchers studying this issue have taken a more thorough/comprehensive evaluation of dairy cow hygiene, including having separate scores for different body regions, including lower legs, upper legs, udder, flank, and belly. Cook (2002) has pointed out the challenges of comparing dairy cattle hygiene between different facility types; namely, cows in freestall barns tend to have dirtier lower legs from walking through alleyways, whereas tiestall cows are likely to have dirtier upper legs and flanks, and loose-housed cows may have a different pattern of manure deposition on their bodies depending on the cleanliness of their lying surface. Despite the limitation of only observing udder hygiene (and the limited sample size of farms in each group), we feel confident that udder hygiene of cows housed on bedded pack systems in the current study was comparable to the more conventional housing systems for dairies in the Northeast. In fact, the farm with the lowest mean average udder hygiene score was a bedded pack farm, and all bedded packs had an average udder hygiene score of less than 2.5.

Other groups looked at cow-level production; but, comparing different types of metric, also, hard to compare this value – so many variables go into milk production per cow (nutrition, breed, seasonality, DIM, component analysis). We have STD150 day milk, others… Bedded pack was 46.9 pounds, overall was 50.0 pounds, freestall was 53.0 pounds. Maybe hard to compare actual production between studies, but can mention other studies that found no difference between CBP and more traditional housing systems…

Udder health outcomes included in the current study, including % cows with any IMI, % cows with chronic IMI, % cows with new IMI, BTSCC, and average LS both unweighted and weighted by production, did not differ significantly between facility types. Although the metrics studied have been varied, overall previous research has also found that udder health and milk quality measures on bedded pack farms are similar to that found on farms traditional using more traditional facility types (Eckelkamp, 2016a; Eckelkamp, 2016b; Black, 2013; Shane, 2010; Barberg, 2007; Lobeck, 2011; Heins, 2019). Specifically, subclinical mastitis prevalence levels did not differ between compost bedded packs and two types of freestall housing in Minnesota and South Dakota, where the percent of cows in a herd with an SCC on test day ≥ 200,000 cells/mL was 33.4, 26.8, and 26.8% for compost bedded packs, cross-ventilated freestalls, and naturally-vented freestalls (Lobeck et. al, 2011). Additionally, Eckelkamp et. al 2016 (Sand bedded…) found no significant difference in subclinical mastitis prevalence in low-SCC CBP vs. sand-bedded freestalls in Kentucky (21.8 and 19.4%, respectively). Barberg et. al 2007b (Performance) found a subclinical mastitis prevalence of 27.7% for 12 CBP farms in Minnesota, which may be more representative of the general population of bedded pack farms in the state, as there were no inclusion criteria around maintaining a low SCC previous to the start of the study. Subclinical mastitis prevalence in the current study was comparable to this previous work, with a prevalence of 26% for farms using a bedded pack and 23.7% for freestall barns. In Brazil, Fávero et. al (2015) found much higher a prevalence of subclinical mastitis (43.8%) and percent new infections (20.9%) for three bedded pack farms than the current study (7 and 26% respectively for the three bedded packs with DHIA data).

With careful management of bedding material and excellent milking hygiene practices, the current study shows that both static and aerobically composting bedded pack barns are capable of achieving excellent milk quality. Three of the five bedded pack farms achieved a BTSCC of below 99,000 cells/mL, and the remaining two were below 200,000 cells/mL. Although historically static bedded packs made of organic material have been considered to be milk quality nightmares, the lowest BTSCC in the study (54,000 cells/mL) was achieved by a bedded pack farm using woodchips and straw that was not actively managing the pack to compost.

As udder health and hygiene for bedded packs compared to tiestalls and freestalls included in the current study, **we feel that bedded pack systems can be considered a viable loose-housing option for the winter (in the Northeast? In Vermont?).** These systems have a number of advantages for producers considering updating their facilities, including a smaller initial investment when compared to a new freestall or tiestall barn (Bewley et al., 2012), although the cost year-over-year for bedding is substantial. Bedded pack systems have considerable advantages from a welfare perspective, as it provides a housing option that doesn’t restrict animal movement, which is an issue of growing concern for both producers and the general public (Barkema et al., 2015). Additionally, bedded packs are designed for cow comfort (Barberg and Endres 2007, Bewley et al. 2017), and prevalence of lameness, foot, and leg injuries in bedded pack systems have been found to be significantly less than tiestalls and freestalls (Barberg and Endres, 2007, Lobeck et al. 2011, Burgstaller et al. 2016). The relationship between decreased milk production and lameness is well documented (Warnick et al. 2001, Green et al. 2002), so there is an additional financial incentive for dairy producers to decrease the prevalence of lameness in their herd. Lastly, manure management and environmental stewardship is a top concern for both dairy producers and the general public (Holly et al., 2018). Bedded systems may provide some advantages over other systems by decreasing the amount of liquid manure storage needed and making the manure drier before it is spread on fields, which may pose less of a risk for run-off into waterways. With no downsides due to hygiene or udder health concerns when properly managed on farms with excellent milking hygiene practices already in place, bedded packs may be an especially good option for small, pasture-based farms in the Northeast both now and in the future.

***Conclusions***

The current study is to the authors’ knowledge the first direct comparison of bedded packs to both tiestalls and freestall of similar size and management styles, for a population of entirely small to midsize organic dairy farms. It is the first publication describing udder health and hygiene on bedded pack systems in the Northeast, which is significant as the performance of a bedded pack system can be greatly influenced by climatic factors. Lastly, previous work has focused on describing bedded packs that are specifically actively managed for composting; by adapting a looser definition of bedded packs included in the study, the current work sheds light on the spectrum of options possible within this loose-housing system utilizing organic bedding material.

Overall, farms with more deeply-bedded cows had improved bulk tank milk quality, as well as better udder health metrics and udder hygiene scores. Unsurprisingly, better udder hygiene was associated with improved udder health measures. Bedded pack systems did not differ significantly in their milk quality, udder health, or hygiene measures when compared to the more commonly used winter housing systems for organic cows in the state. Bedded packs can therefore be considered as a viable option for pasture-based herds looking for a more affordable loose-housing system.